

ACOUSTIC EMISSION FROM A GROWING CRACK

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## ABSTRACT

An analytical method is being developed to determine the signature of an acoustic emission waveform from a growing crack and the results of this analysis are compared to experimentally obtained values. Within the assumptions of linear elastic fracture mechanics, a two dimensional model is developed to examine a semi-infinite crack that, after propagating with a constant velocity, suddenly stops. The analytical model employs an integral equation method for the analysis of problems of dynamic fracture mechanics. The experimental procedure uses an interferometric apparatus that makes very localized absolute measurements with very high fidelity and without acoustically loading the specimen.

## INTRODUCTION

Acoustic emission testing is a method of nondestructive evaluation that detects stress wave emissions from fracture and deformation processes within a loaded body. This testing differs from other methods of nondestructive evaluation in that the signal being detected is released from within the specimen rather than being created by the nondestructive testing method. The technique offers a distinct advantage over more conventional nondestructive testing techniques because it allows for the real time monitoring of in-service structures. Some of the potential source mechanisms of acoustic emission include: crack propagation and arrest, fretting among fracture surfaces, dislocation movement, microcracking, twinning and phase transformations. In addition to these failure related mechanisms, other phenomena such as fastener fretting, structural vibration and electromagnetic noise can create spurious signals which are detected by the acoustic emission instrumentation. Of fundamental importance for the advancement of the current state of acoustic emission technology is the isolation and identification of the signal from a growing crack. The technology for detecting and locating internal sources of acoustic emission is well established. However, acoustic emission signals contain a vast amount of additional information about the source of the emission and the condition of the material being examined. The signal is not only influenced by its source but also by the specimen geometry (which effects the stress wave propagation from the source to the sensor) and the characteristics of the sensor. A thorough understanding of each of these factors is necessary in order to accurately interpret the acoustic emission signature. The proposed solution procedure will attempt to apply methods from dynamic fracture mechanics and wave propagation to the quantitative characterization of acoustic emission signals.

This work complements previous studies by providing a development of the analytical form of an acoustic emission waveform caused by a crack growth event. An advantage of the proposed analysis is that the source for the acoustic emission signature is an actual crack propagation event and not a simple point source model. The propagation of the crack greatly influences the stress field in the vicinity of the crack tip, causing stress wave fronts to radiate into the body and on the crack surface. Acoustic emission testing detects these stress waves at the body's surface and relates the signal back to the corresponding crack propagation event. The proposed method uses an integral equation technique for the analysis of problems of dynamic fracture mechanics developed by Jacobs and Bieniek [1]. The problems of dynamic crack propagation have been the subject of numerous investigations in the past several years. A majority of the work

has been summarized in review articles by Achenbach [2, 3], Freund [4, 5], Rose [6] and in the book by Kanninen and Popelar [7]. The preceding works have primarily been concerned with the determination of the dynamic stress field in the vicinity of the moving crack tip. They did not examine the effect of the propagation and arrest of the crack tips throughout the entire body. Freund [8] determined the pressure discontinuity radiated out from a crack tip when the crack, which is initially at rest, begins to grow. Rose [9] calculated explicit formulae for the stress discontinuities radiated by a suddenly starting two dimensional crack under tension for application to acoustic emission testing. Achenbach and Harris [10] examined the acoustic emission signals from a semi-infinite crack of arbitrary shape using the elastodynamic ray theory. Harris and Pott [11] investigated the surface motions excited by fracture processes at the edge of a buried crack.

Previous investigators worked to identify the acoustic emission signal from a crack propagation and arrest source. Summaries of this work appears in Eitzen and Wadley [12], Pao [13] and in a book by the American Society for Nondestructive Testing [14]. Hutton, Friesel, Graham and Elsley [15] successfully characterized acoustic emission signals in laboratory investigations using statistical pattern recognition algorithms which characterize signals empirically on the basis of features observed in a large number of events. These methods are strictly empirical in nature and provide little insight into the fracture process. Other investigators concentrated on the geometrical effects of the acoustic emission signal. Pao, Gajewski and Ceranoglu [16] and Ceranoglu and Pao [17, 18, 19] examined the propagation of an acoustic emission signal in an elastic plate. These solutions are not empirical, but are based on the generation and propagation of elastic waves in a wave guide. The solutions, which examine point sources inside an infinite elastic plate, use a generalized ray theory and integral transform techniques. They provide numerical results for the surface displacements for a variety of dynamic nuclei of strains, including concentrated forces and couples. Individual or combinations of these sources are used to model the dynamic processes of material defects. Kim and Sachse [20, 21, 22, 23] investigated both the analytical and experimental signature of an acoustic emission waveform.

#### ANALYTICAL METHOD

The integral equation in the present application is in two variables, a spatial coordinate ( $x$ ) and time ( $t$ ). Within the assumptions of linear elastic fracture mechanics, the dynamic stresses caused by a prescribed crack growth event in an infinite two dimensional body are calculated. These results can be used to calculate displacement as a function of time at any point within the body. The first step of this analysis, summarized in [24, 25], uses an influence function to formulate an integral equation that expresses the boundary conditions in the plane of the crack. The steps for the calculation of the dynamic stresses are as follows:

- (a) Determination of the influence (or Green's) function of the problem, which is the dynamic displacement of an elastic half-space subjected to a unit concentrated impulse acting at the point of, and normal to, its edge.

- (b) Formulation of the integral equation of the problem. This integral equation, with the influence function as the kernel and the normal stress in the plane of the crack as the unknown function, expresses the boundary conditions in the plane of the crack - a stress free crack surface and continuity of displacements outside of the crack.

- (c) Solution of the integral equation.

The solution presented is for a semi-infinite crack that is symmetrically loaded (Mode I). First, solve for the influence function,  $U_y(x-x', t-t')$ , in closed form using integral transform methods. This is accomplished by taking a one-sided Laplace transform in time  $t$  and a two-sided Laplace transform in  $x$ . In the transform space, the two uncoupled partial differential equations are replaced by two uncoupled ordinary differential equations. The determination of the inverse transformations of the required surface displacement component is accomplished using the Cagniard-de Hoop method.

To formulate the integral equation, assume a crack exists at time  $t=0$  with its tip located at  $x=a(0)$  and  $y=0$ . For time  $t>0$ , the crack moves from  $x=a(0)$  to  $x=a(t)$ . The two relevant boundary conditions are that the newly formed crack faces are stress free and that the vertical displacement in front of the moving crack tip is zero. Both of these boundary conditions are met by:

- (a) Removing the existing known static stress,  $\sigma_{yy}=P(x)$ , and assuming that instead a new unknown time dependent stress,  $\sigma_{yy}=F(x,t)$ , develops.
- (b) Requiring that the new stress distribution be such that there is vertical displacement continuity in front of the moving crack tip.

The continuity boundary condition can be expressed in terms of the influence function,  $U_y(x-x', t-t')$ , as:

$$-\int_0^t \int_{-\infty}^{\infty} P_s(x') U_y(x-x', t-t') dx' dt' + \int_0^t \int_{-\infty}^{\infty} F(x', t') U_y(x-x', t-t') dx' dt' = 0 \quad (1)$$

The above is a Volterra integral equation of the first kind in the variables  $x$  and  $t$ . To provide a simple solution of this integral equation, assume some spatial form of the unknown stress distribution,  $F(x', t')$ . Assume, further, that the spatial distribution of  $F(x', t')$  contains a square root singularity at its tip location  $a(t')$ , which is the same spatial form of stresses as a static crack with its tip located at  $a(t')$ . However,  $F(x', t')$  must contain an unknown time function,  $K(t')$ . Thus, the unknown stress in front of the moving crack tip is assumed to have the spatial form of its corresponding static crack multiplied by some unknown time function. It should be noted that due to the presence of step functions in the influence function, the infinity limits in the  $x'$  integration of the integral equation can be replaced by the distance that the fastest wave will travel in the elapsed time,  $t-t'$ .

The direct quadrature method [26, 27] is used for the solution of the integral equation. There are, however, two refinements which are necessary in the numerical solution of the integral equation. The first refinement is a "subdivision" of the time step,  $\Delta t$ , in the evaluation of the numerical

integrations, while the second is a mid-point product integration scheme [28] which is employed to handle the singularity of the kernel at  $t'=t$ . For the steady state case of a crack propagating with a constant velocity, the calculated value of  $K(t)$  is a constant that is only a function of the crack tip velocity. As the crack tip speed increases, the corresponding constant value of  $K(t)$  will decrease. The results of the case for a crack that suddenly stops after propagating is that the calculated value of  $K(t)$  discontinuously jumps to the value of the corresponding static stress; there is no transition zone and the stress never increases above the value for an equivalent static crack.

The displacement at any point within the infinite body is determined using the previously calculated dynamic stress,  $F(x,t)$  and two new influence functions  $U_{xy}(x-x',y,t-t')$  and  $U_{yy}(x-x',y,t-t')$ . These influence functions represent the horizontal displacement  $u_x$  and the vertical displacement  $u_y$ , respectively, at point  $(x,y)$  within an elastic half-space that is subjected to a vertical unit impulse surface loading at  $x'$ . The solution for these new influence functions is accomplished using integral transform techniques and the inversion is again performed using the Cagniard-de Hoop method. Convolution integrals are developed for the vertical and horizontal displacements for any point,  $(x,y)$ , within the body by determining the displacements due to the application of the previously calculated dynamic stress distribution and the removal of the initial static stress distribution. The displacements are given by:

$$u_x(x,y,t) = - \int_0^t \int_{-\infty}^{\infty} P_s(x') U_{xy}(x-x',y,t-t') dx' dt' + \int_0^t \int_{-\infty}^{\infty} F(x',t') U_{xy}(x-x',y,t-t') dx' dt' \quad (2)$$

$$u_y(x,y,t) = - \int_0^t \int_{-\infty}^{\infty} P_s(x') U_{yy}(x-x',y,t-t') dx' dt' + \int_0^t \int_{-\infty}^{\infty} F(x',t') U_{yy}(x-x',y,t-t') dx' dt' \quad (3)$$

These integrals can be evaluated numerically. Difficulties arise in the  $x'$  integration due to both the integrands' complexity and the presence of singularities. There are singularities of different strengths and discontinuities associated with the moving crack tip, the original crack tip and the various wave fronts. Each of these singularities must be investigated separately to properly evaluate the integrals. To avoid numerical problems, the final integration technique will involve separating the  $x'$  integration interval into singular and non-singular regions. To evaluate the integral in the area of the singularity, a hybrid method is proposed. Following Davis and Rabinowitz in [71], the singularity is dealt with by breaking up the original integral in the singular region into two new integrals. One of the new integrals contains the singularity, but it can be evaluated analytically; the second integral, which is evaluated numerically, is non-singular since its integrand will approach zero as the potential singular point is approached.

## EXPERIMENTAL RESULTS

The second step is to compare the results of the analytical model with experimentally obtained waveforms. It should be noted that the analytical procedure being developed is for the time prior to the arrival of stress waves

reflected from the test specimen's boundary so it is invalid for the time period after the fastest reflected waves interfere with the unadulterated signal from the crack propagation event. The experimental test procedure examines an existing crack that is forced to propagate a short distance and be arrested. The specimen used is a screw loaded, wedge opening load sample, where the crack unloads as it extends and the propagation is arrested before complete failure occurs. The specimens are made of a brittle material with a low fracture toughness, poly methyl methacrylate. Its optical transparency permit the size, geometry and location of the cracks to be readily determined. Cracks in these specimens are initiated by driving a sharp blade into the notch of the specimen; further propagation is produced by tightening the screw.

A high sensitivity heterodyne interferometer is used to detect acoustic emission events. This optical device permits the high fidelity localized measurement of velocities from acoustic emission events arriving at various points on the sample surface. Since this type of measurement does not acoustically load the sample, the event being observed is undisturbed by the measurement process. The most commonly used acoustic emission sensor is the piezoelectric transducer. Since it must be used in direct contact with the specimen, the transducer will disturb the process being measured and the signal response will be averaged over this area of contact. Additional limitations of these sensors is that it is difficult to manufacture a truly broad band transducer, they are extremely difficult to calibrate accurately and there are many questions as to exactly what the transducer is measuring.

The specimen face opposite the crack is polished and placed in the interferometer and becomes one mirror surface. The beam striking the face is approximately 1.5 mm in diameter and samples the average displacement taking place over this region, which is much smaller than the wavelength of the acoustic events being observed. The operation of the heterodyne interferometer is described in [30]. Briefly, single frequency laser light is split into two components using an acousto-optic modulator. These two components, which are separated in frequency by 40 MHz, are sent along two arms of an interferometer one of which contains the sample being monitored. The beams are recombined on the surface of a photodetector where they beat together at a frequency of 40 MHz. Phase shifts in the light reflected from the sample surface result in equivalent phase shifts in the 40 MHz beat signal received at the photodetector. This carrier signal can then be demodulated to determine the time dependent displacement occurring at the sample surface. The detection system has a band width of 10 MHz which is further limited to the spectral region 0 to 2 MHz in order to reduce the noise in the signal. All signals are acquired on a digital oscilloscope and stored for later processing. The crack velocity is measured with conventional crack propagation gages. This also aids in determining the time difference between the crack growth event and the arrival of its signal at the measurement point. This is accomplished by pretriggering the measurement system on the start of the crack propagation event and not the arrival of the first wavefront.

## DISCUSSION

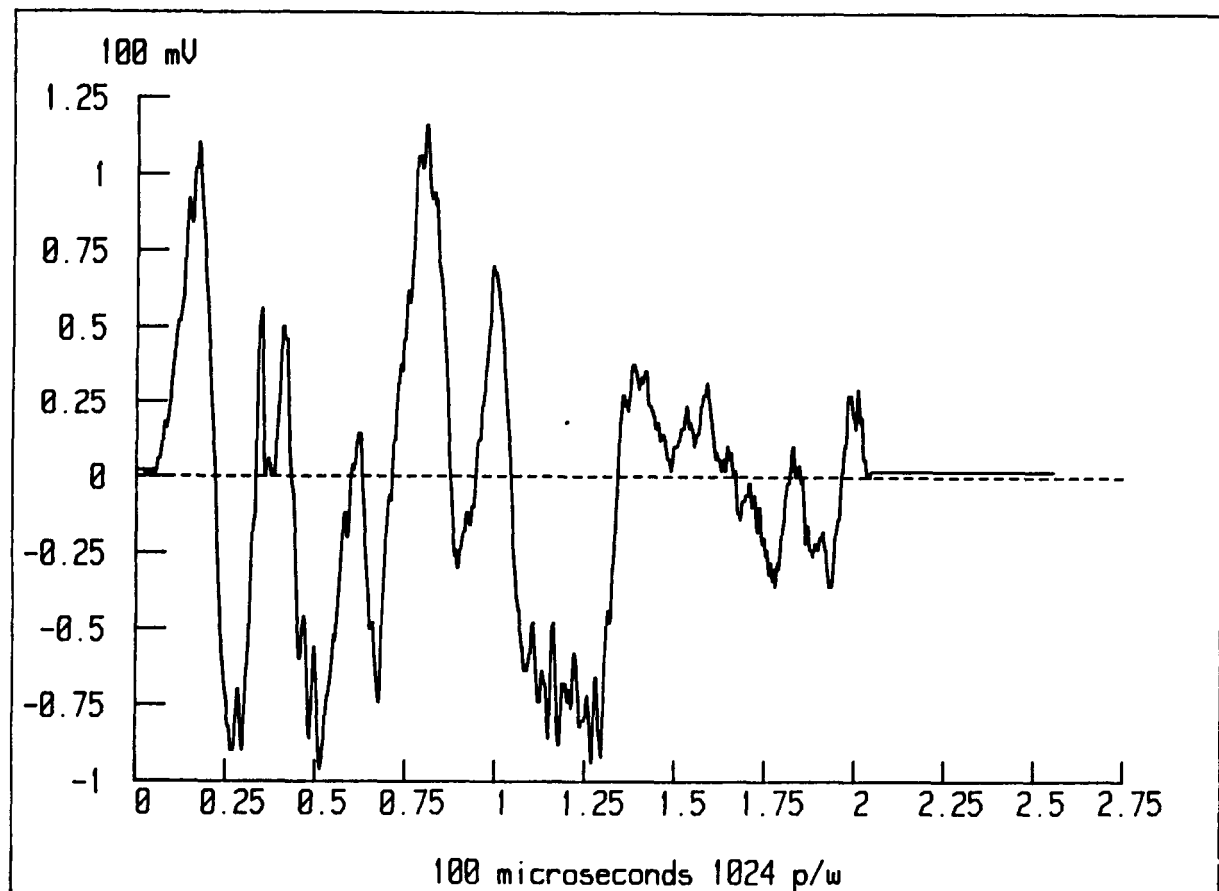
A characteristic crack emission is shown in figure 1. Care must be taken to calculate the effect of wave reflections and mode conversions that occur at the specimen's boundaries. The experimentally obtained waveforms will be

interpreted using the results of the analytical model being developed in the first task. Since the dynamic stress calculations indicate sharp stress discontinuities associated with the starting and stopping phases, it is anticipated that there will be corresponding displacement variations that will become evident in the experimental modeling. Anomalies in the fracture behavior of the specimen included out of plane growth and some crack tunneling. The out of plane growth could be caused by twisting due to the bearing stress between the bolt and the lower crack surface. Further development of the analytical model is necessary before the experimentally obtained waveforms can be interpreted.

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Figure 1: Acoustic Emission Signal from a Growing Crack



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